THE GALILEO/MARS 013 SERVER/ULYSSES COINCIDENCE EXPERIMENT

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From March 21 to April 11, 1993 the Galileo, Mars Observer and Ulysses spacecraft were tracked in a coincidence experiment, searching for low-frequency (millihertz) gravitational radiation. The Galileo (GLL) observations were made with an S-band (≈2.3 GHz) radio link, the Ulysses (ULS) observations with a hybrid S-band uplink/S-X band downlink (X band is about 8.4 GHz), while the Mars Observer (MO) data were X-band up- and downlink. The three experiments thus had unequal instrumental sensitivity to a major noise source (plasma scintillation noise). The sun-earth-spacecraft angle and two-way light times were also unequal, giving rise to different Fourier passbands and different responses to a wave coming from a given point on the celestial sphere. This GLL/MO/ULS experiment is the only low-frequency coincidence experiment to date and very strong suppression of systematic effects that were not common-mode in the three time series was possible. This paper discusses an initial analysis for periodic and quasi-periodic radiation, including the first use of the time-dependence of the tracking geometry to refine positions of candidate low-frequency sources and the first use of polarization information afforded by simultaneous observations. We note some implications of these observations for the very-sensitive Ka-band (≈32 Ghz) gravitational wave' experiment planned for the Cassini spacecraft.

1 Doppler Tracking in the Low-Frequency Band

1.1 Three-Pulse Response

In the spacecraft technique the earth and a distant spacecraft act as separated test masses. The Doppler tracking system measures the relative dimensionless velocity of the earth-spacecraft system

$$2\frac{\Delta v}{c} = \frac{\Delta \nu}{\nu_0} = y \tag{1}$$

as a function of time; $\Delta\nu$ is the perturbation of the Doppler frequency from ν_0, the nominal radio frequency. A gravitational wave of strain amplitude h incident on the system causes small perturbations in the tracking record. These perturbations are of order h in y and are replicated three times in the

the Doppler data[1]. That is, in the idealized case the gravitational wave signal in the observed Doppler time series is the convolution of the incident component of the wave

$$s(t) = (1 - \mu^2)^{-1}\mathbf{n} \cdot [h_+(t)\mathbf{e}_+ + h_\times(t)\mathbf{e}_\times] \cdot \mathbf{n} \tag{2}$$

with the three-pulse response function

$$r(t) = \frac{\mu - 1}{2}\delta(t) - \mu\delta(t - (1 + \mu)L/c) + \frac{1 + \mu}{2}\delta(t - 2L/c). \tag{3}$$

Here μ is the cosine of the angle between the earth-spacecraft vector and the gravity wavevector, L is the earth-spacecraft distance, $\mathbf{n}$ is the unit vector from the earth to the spacecraft, $h_+(t)$ and $h_\times(t)$ are the gravity waveforms for each polarization and $\mathbf{e}_+$ and $\mathbf{e}_\times$ are transverse, traceless polarization tensors[1,2,3]. The sum of the three pulses is zero; hence burst waves having a duration longer than about L/c overlap in the tracking record and the net response cancels to first order. The tracking system thus has a passband where it has maximum sensitivity. (Below about c/L, by pulse cancellation, the response falls off according to $(2\pi f L/c)(1 - \mu^2)$. Thus for an interplanetary spacecraft 1-2 AU from the earth the low-frequency response degrades below about 0.001 Hz. Thermal noise in the radio system and the short-term stability of the frequency standard to which the Doppler system is referenced degrades the high-frequency response above $f \approx 0.1$ Hz.)

1.2 Directionality and Polarization Information

The Doppler response to a gravitational wave depends on the wave's arrival direction and polarization state. For example, when μ is close to unity, the magnitude of the first pulse is close to zero and the second and third pulses merge together. The practical case is complicated by time variation of the earth-spacecraft geometry. For waves from a given direction in space, μ varies with time over the course of the three-week observation due to changes in the direction of the earth-spacecraft vector. This deterministic and relatively slow variation causes amplitude and phase modulation of periodic and quasi-periodic waves coming from a distinct direction in space. The modulation is different for different source positions on the celestial sphere. Also the distance to the spacecraft changes in a deterministic way over the duration of the experiment, T. This variability in the two-way light time, $T_2 = 2$ L/c, also causes modulation of a continuous wave. Although these effects complicate the analysis, the modulation provides a very useful known signature which can be exploited to provide source position for incident periodic and quasiperiodic waveforms.

Simultaneous tracking of three spacecraft allows polarization information to be used to distinguish periodic signals of astronomical origin from noise events[3]. For an elliptically polarized sinusoidal wave of amplitude H and angular frequency w coming from a source at right ascension and declination (a, d) and sensed through the Doppler tracking of a spacecraft at right ascension and declination (α, δ), the signal waveform (prior to convolution with the three-pulse response) is[3,4]

$$s(t) = H(1-\mu^2)^{-1}(A^2+B^2)^{1/2}\sin(\omega t+\phi) \tag{4}$$

where $A = \sin(\gamma)\cos(\phi)(D^2 - E^2) + 2DE\cos(\gamma)$, $B = \sin(\gamma)\sin(\phi)(D^2 + E^2)$, $D = -\cos(d)\sin(\delta)\cos(a-\alpha) + \sin(d)\cos(\delta)$, and $E = \cos(d)\sin(a-\alpha)$. If, through the $\mu(t)$ and $T_2(t)$ modulation of the signal, a direction to the source is found then the amplitudes of the signal in the the three spacecraft time series give polarization constraints. In the case where one spacecraft gives a candidate detection of a sinusoid from direction (a, d) and the others do not, then one can ask if a true signal could be hidden in the other two time series because of poor polarization match (or poor three-pulse transfer function). If there is no polarization state (γ, ϕ) that gives $(A^2 + B^2)^{1/2}(1-\mu^2)^{-1}$ large for one spacecraft but simultaneously small for the other two then the candidate cannot be due to an elliptically polarized wave of astronomical origin.

2 The Galileo/Mars Observer/Ulysses Experiment

The spacecraft were tracked from March 21 to April 11, 1993, in a low-frequency coincidence experiment. Galileo had an S-band (approximately 2.1 GHz uplink, 2.3 GHz downlink) radio system on both the up and downlinks. Mars Observer had X-band (approximately 7.2 GHz uplink, 8.4 GHz downlink) radio links on both up- and downlink. Ulysses had a system with S-band uplink and simultaneous S-band and X-band downlinks[5]. Of course the lower radio frequency (S-band) is affected more by phase scintillation caused by plasma irregularities along the line-of-sight (ionosphere, solar wind)[2,5]. The Mars Observer observations were the first X-band up and downlink observations made in the antisolar hemisphere and were the least affected by solar plasma. For the observations reported here, phase scintillation caused by propagation through the irregular media between the tracking station and the spacecraft (troposphere, ionosphere, solar wind) was nonetheless the dominant noise source for all three spacecraft. Galileo observations were at relatively low radio frequency, and solar plasma phase scintillation was the main noise source. Mars Observer, our most sensitive tracking link, was limited by a combination of plasma and tropospheric scintillation[6]; the power spectrum of y, expressed as equivalent sinusoidal strain amplitude[5], varied between about $1 X 10^{-15}$ and $5 X 10^{-16}$ over the Fourier band (0.001 -0.05 Hz).

The antennas of the NASA Deep Space Network (DSN) have been carefully engineered for excellent phase stability[5,7,8]. Open-loop recordings (i.e., recordings of the pre-detection electric field of the downlink) were made of the Mars Observer downlink as it was tracked with the DSN 34 meter High Efficiency antennas. Doppler frequencies were then extracted in software. Galileo was tracked with the 70 meter DSN antennas, while Ulysses was tracked with the 34 meter DSN Standard antennas. Doppler frequencies were read out in real-time with the closed loop tracking system for both Galileo and Ulysses. Hydrogen maser frequency standards were used as frequency references for the microwave systems of all the tracking antennas, thus frequency standard noise was at a negligible level.

At the level of sensitivity of this experiment, the Doppler time series of fractional frequency fluctuation, y(t), can be modeled as due to the sum of gravitational waves, propagation noise (plasma and troposphere), clock noise, thermal noise, and systematic effects. The signal enters through the three-pulse transfer function (above); the noises enter through different transfer functions[2,5,10] The differences in the transfer functions of signal and noises can be used to improve signal-to-noise ratio[9].

The directions to the spacecraft and the two-way light times T_2 changed slowly over the course of the observations. The solar elongation angles varied from 101° to 92° (Mars Observer), 155° to 138° (Galileo), and 146° to 127° (Ulysses). T_2 varied between 937 to 1128 seconds for Mars Observer, 669 to 915 seconds for Galileo, and 4015 to 4146 seconds for Ulysses.

3 Periodic and Quasi-Periodic Waveforms

3.1 *Search Procedure*

Here we discuss only analysis for periodic and quasi-periodic waves. Such waves might be produced by coalescing binaries at different points in their evolution[2,4,11,12,13]. Observationally[11], the character of the waveform changes depending on the evolution of the wave's phase over the observing time, 1. Our analysis approach is different depending on whether the wave can be regarded as a "sinusoid" (signal frequency changes by less than the resolution bandwidth of the experiment in time T), a "linear chirp" (signal frequency changes by more than a resolution bandwidth, but only linearly with time over the duration of the experiment), or a more complicated waveform.

Our search for periodic and quasi-periodic gravitational waveforros was done in two stages. 'l'he first stage was to do a suboptimum but computationallefficient analysis to exclude candidates that were unlikely to produce significant outputs in an exact analysis. Those candidates that remained were then passed through the second stage: exact matched filters that took into account the time-variability of T_2 and μ with respect to a set of assumed source directions. (For the analysis reported here, we approximated an all-sky search by taking as candidate source positions the 20 vertices of a dodecahedron projected onto the celestial sphere.)

This two-stage analysis procedure was necessary because exact matched filtering for all candidate signals is computationally impractical even for relatively simple waveforms. For example, an all-sky matched filter search for linear chirp waveforms- each wave characterized by an initial frequency f_0 and a frequency derivative $\beta = df/dt$–requires a very large number of filters. There are roughly $f_{ny}/\Delta f \approx$ 90,000 initial frequencies (where f_{ny} is the Nyquist frequency = 0.05 Hz in this experiment, and Δf is the frequency resolution = 1/T. We considered 20 candidate source directions on the celestial sphere and about $(96/11 f_{ny} T)^{1/2} \approx$ 900 values of β (not all of which give uncorrelated filter outputs, however). Thus, for this experiment, a brute force search for linear chirp waveforms would require of order a billion matched filters for each spacecraft. Because of the time variation in T_2 and earth-source direction, the three-pulse transfer function is not time-shift invariant, limiting the use of fast algorithms to realize these filters. Implementing a brute-force time-domain matched filter search for just this one waveform would take decades of computer time with mid-1990s workstation technology.

To address the issue of completeness in a two-stage search for sinusoidal waves, we performed a simulation (for the Mars Observer geometry) comparing the signal- to-noise ratio (SNR) of exact matched filter analysis with that of simple spectral analysis. The simulation assumed gravitational wave frequencies uniformly distributed over (0.001-0.05112). Suboptimum spectral analysis only rarely gave SNRs less than 0.4 of that of matched filtering for the Mars Observer geometry. Put another way, real signals identified through spectral analysis would only rarely have SNRs boosted by more than a factor of 2.5 in an exact matched filter analysis.

3.2 *Sinusoidal Waveforms*

Sinusoids, the prototype periodic waveform, are operationally defined as sine or cosine waves that have negligible frequency evolution over the approximately 3 week observing interval. The first stage analysis is to produce the power spectrum and compare the power at each Fourier bin with the power in a locally smoothed version of the power spectrum[5]. In the absence of a signal, these norrealized powers are exponentially distributed. The histograms of normalized spectral power were indeed close to exponential with unit variance, with the largest observed lines in the spectra having SNRs ranging from 13.6 to 15.0 for the three time series. One false alarm was expected at an SNR of about 14.8, thus these histograms did not show any unexpectedly large spectral lines. The frequencies of lines having normalized spectral power greater than 6 were saved for the second stage of the analysis. (Since the simulation showed that SNR boosts by more than a factor of 2.5 were rare, a real signal observed with SNR less than 6 would be unlikely to be raised to an '(interesting" SNR of greater than 15 through matched filtering. Thus, for sine waves, we could do an almost complete search by prequalifying f_0's with spectral analysis and then applying matched filters to only the fraction $e^{-6} \approx 0.0025$ of the frequencies associated with the strongest spectral lines.)

'The matched filters gave undistinguished peak SNRs for Mars Observer and Galileo. For the Ulysses data set, however, the peak SNR was 19.9 for one particular sinusoid ($f_0 = 0.0132917$ Hz), from the direction of the dodecahedron vertex that projected to $\alpha = 0°$, $\delta = +69.1°$. Although a sinusoid this strong at this high a frequency implies an improbably nearby source, an SNR this large is formally unlikely based on noise only and must be considered.

Since the geometry was known (vectors to spacecraft, direction to candidate source), we searched for gravitational wave elliptical polarization states[3,4] that couple well to Ulysses and simultaneously poorly to Mars Observer and Galileo. The result is that there are no polarization states that do this and so we can exclude this as a false alarm based solely on our observations.

In previous experiments[5,11] we have used subsets of the data–based e. g. on inclusion or exclusion of specific stations, inclusion or exclusion of specific transmit/receive pairs, or on temporal partitioning of the data set-to identify systematic effects that have given false alarms. This is the first example of multiple spacecraft data sets and consideration of polarization to disqualify a candidate event.

3.3 *Linear Chirps*

An analogous two-stage procedure was used to search for linear chirps. The first stage was to preprocess[13] each time series by multiplying by $exp(-i\pi\beta t^2)$ and then perform spectral analysis as in the sinusoidal case. This was done for a set of candidate chirp rates, β, between zero and β_{max} (chosen such that the higher derivatives from an astrophysically clean system would begin to be importantly' [13].) This first stage produced histograms of normalized power close to the exponential distribution expected for noise only. The (f_0,

β) pairs giving rise to SNRs greater than 12 in this analysis were then used in a matched filter analysis, with the 20 assumed directions indicated above. The peak SNRS of the matched filter analysis (on the three time series separately) ranged between 20.0 and 23.6. This is to be compared with the SNR for one false alarm of ≈ 22. We have no credible linear chirp candidates.

3.4 *More Complicated Chirp Waveforms*

Binary astrophysical systems close to coalescence will radiate waves having significant second and higher derivatives of the wave frequency over the observing time. A computationally practical first stage analysis is to resample the time series synchronous with the phase of the wave, converting it to a periodic signal[11,14]. Spectral analysis can then to used to find candidate signals. This is a two-parameter search (e.g., frequency of the wave at the start of the observation, f_0, and Newtonian time-to-coalescence, τ). This is suboptimum because it does not account for the three-pulse response, the source direction or amplitude modulation[13]. We used this procedure on the three time series (restricting ourselves to τ larger than 1.1 times the duration of the experiment) getting exponential histograms for normalized power expected expected for the noise-only case. Extreme events in the histograms were observed at SNRS of 22.2-23.4, consistent with our expectation of 1 false alarm at SNR ≈ 23, given the number of parameters we searched. The second stage of analysis, using matched filtering for coalescing binaries from astrophysically clean binary systems, is not yet complete.

4 Implication for Cassini Gravitational Wave Experiment

The Galileo/Mars Observer/Ulysses experiment was the first coincidence experiment in the low-frequency band. Variations in the two-way light times and orientations of earth-spacecraft vectors over the ≈ 3 weeks of observations introduced systematic modulation in any real signals, allowing positional information to be determined. These modulations, plus additional constraints that three spacecraft give on the polarization state of candidate waves, have been used in an initial search for periodic and chirp radiation. For sinusoidal radiation, the different responses of the three spacecraft to elliptically polarized waves was also used to disqualify a candidate detection.

The sensitivity of this experiment was set by propagation noise (troposphere and charged particle). Future experiments using links at higher radio frequencies. in particular the experiment on the Cassini spacecraft, will essentially eliminate plasma scintillation. Tropospheric scintillation, dominated by water vapor turbulence, should be largely correctable using coincident water vapor radiometer observations. The ultimate sensitivity of the experiment will probably be set by residual error in the tropospheric calibration, noise introduced by mechanical motions within the antenna itself, and by low-level systematic errors. Cassini's sensitivity to periodic waves should be more than an order of magnitude better than Mars Observer's over the whole low-frequency band; at selected frequencies, exploitation of noise source transfer functions should allow even better sensitivity.

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